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MONITORING COASTAL LANDSLIDES ALONG THE NORTHEAST BLACK SEA OF BULGARIA USING SAR DATA

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Abstract

The geological conditions along the Northeast Black Sea coast of Bulgaria are favourable for landslides emergence and development. Those processes have been rigorously documented in the last fifty years by Earth science researchers. Their efforts contributed in a broader context to the landscape conservation and to mitigate the risks for the population caused by the mentioned surface disruptions. In this paper the obtained results record the temporal behaviour of several landslides located in stated region during the last five years. The main data source to monitor the mentioned landslides is data from synthetic aperture radar (SAR) instrument processed by the differential interferometric SAR (DInSAR) method. The produced results were validated by means of global navigation satellite system (GNSS) measurements carried out at purposely created geodetic networks, satellite images with high spatial resolution and digital images obtained by unmanned aerial systems (UASs). The results presented in this paper unambiguously confirm the usability of the produced information for the local authorities and other stakeholders thus contributing to the improvement of landslide risk management practices and to the better planning of the territory where the researched landslides are located.

1. Introduction

The geophysical hazards, such as earthquakes, floods, landslides, severe storms, droughts to name a few, indisputably have negative impact on the landscape and on the ecosystems. To this end the protection from them is crucial in saving human lives, keeping the animals' habitats, and decreasing the economic losses not only at national, but at continental level, since it is often the case that single event is affecting more than one country [1]. At present the data delivered by large number of sources e.g. remote sensing Earth observation from satellites or UAS, in-situ observations and measurements largely increases the accuracy of the data that support the development of new geophysical models for alleviation of the effects from the said negative events. On the other hand, the modern geographic information systems (GIS) taking advantage of the increased processing and communicational capabilities of supercomputers, workstations, and mobile devices allow handling of large data volumes needed by the models. All said eventually results in better understanding of the georisk processes and their management by the authorities at local and national level. In order to facilitate the understanding of the mentioned landslide processes we decided to investigate several areas located along the coastal zone of Northeast Bulgaria known to have suffered by such events [2]. To this end we proposed and implemented an approach that took advantage of large number of data sources (available or emerging) that will lead to more complete identification and registration of the future landslides activation in the researched region.

In this context it was necessary to find more sources of regularly updated and reliable information with regard to the ground surface motions in the investigated area, which was one of the tasks we had to cope with initially and is still ongoing. In this paper we realized an integrative approach based on variety of sources the SAR and GNSS being the main ones, but supported by other such as modern geological maps, maps of land cover/land use, high accuracy digital elevation models (DEMs), data from local UAS campaigns and excerpts from national orthophoto coverage, reports from regional authorities [3]. Such an approach, according to the best of our knowledge, has not been implemented before in investigation of landslide processes registered at the coastal zone of Northeast Bulgaria or in other area of the country.

For the whole Black Sea coastal zone of Bulgaria, it was estimated that the landslide areas occupy about 13% of its length. In addition, it should be highlight that the said unfavorable processes also decrease the biodiversity as well as the quantity and quality of the ecosystem services provided by the techonogenically overwhelmed areas of the landscape consisting of industrial, residential and touristic buildings [4].

In this paper the authors have narrowed their research only on the area along the seashore zone between the town of Varna and the Kaliakra cape. According to [3] in the said strip found are 124 stabilized, semi-stabilized and active landslides. The overall conclusion is that for the development of landslide processes in the studied region those processes haven’t activated abruptly, and no large impact was observed for the investigated period January 2015 to September 2021[1]. On the other hand, for the majority of the researched zones the surface movements are still ongoing.

The all above stated (landslides occurrence, technogenic load, landscape preservation) prompted the authors to set the main focus of this paper on underlining the possibilities for regular monitoring of the landslide processes occurring on coastal zone in NE Bulgaria provided by processing satellite data from SAR instrument onboard the ESAs’ Sentinel-1 (S-1) mission. The main advantages offered by the mentioned data source are - large area for observation; data provision at fixed intervals; open data policy, accessible and validated software for processing.

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[1] This period is defined by the terrain observations and measurements made by the authors.

The aim of the research is to summarize the achievements of the authors by showing the results from their research concerning the integral and complementary use of multisource data to deliver up-to-date, reliable, and frequently updated information to the competent authorities and to the public with regard to the ongoing surface deformations caused by recent surface movements at the monitored landslide areas. In this research the authors took advantage of the joint use of data from GNSS and SAR.

2. Region of study and geological setting

2.1. Geography and climate

The researched region is located in northeast part of the Balkan Peninsula known with numerous landslides found at the cliffs along sea shore. The main factors that cause their activation are as follows – the sea erosion the rainfalls and snow melt (leading to fluctuations in groundwater levels); the seismic events; anthropogenic impact. According to the Global Earthquake Model [5] the seismic hazard measured in PGA for the area is relatively high 0.08 to 0.20 (g), but in the last years no large landslide event could be directly related with seismicity. The impact of the rest factors on the landslides' activation will be discussed later-on in the section 5.

The northern part of Bulgarian Black Sea coast includes the coastal zone north of the city of Varna ending at Bulgarian-Romanian border. This zone includes ancient and modern landslides having different degrees of activity. The factors mentioned in the previous paragraph trigger landslide activity in this region causing slow horizontal and vertical movements of the Earth's surface. Depending on the degree of the impact, the geological structure and lithological composition of the rocks along with their engineering geological properties, two large landslide zones can be separated – Varna and Balchik areas. During the 60s of the last century two types of landslides were differentiated along the Varna and Balchik coasts – of circus type for the Varna coast, and linear-stepped, package type for landslides for the Balchik coast [2]. The geology engineers connected the separate types of landslides with the features of coarse-sandy facies in the Varna area (Dalgiya Yar) and with clay-marl - in the Balchik area ("Fish-Fish" and "Thracian Cliffs") [2].

3. Materials and methods

3.1 Interferometric processing of SAR data

Radar systems are active remote sensing instruments operating in the microwave part of the electromagnetic spectrum (EMS) used on aircrafts and satellites. The side looking antenna sends pulses at precise wavelengths (currently used are L, C and X bands of EMS see [6] for details) to surface targets and registers the backscaterred signal, which is composed of amplitude and phase. The magnitude of the amplitude reflects the physicochemical properties of the target surface such as roughness, while the phase corresponds to the distance to it. The modern radar systems are imaging radars with synthetic aperture, which simulates large antenna in order to increase the spatial resolution of the produced image. This concept is illustrated on Fig. 1. The smallest imaged surface area (called “ground element”) registered by the SAR instrument is product of the range and azimuth in sensor geometry and only after appropriate processing ending with transformation to specific datum is converted to an image pixel that corresponds to an area of the Earth’s surface. The mentioned imaging geometry has some drawbacks known as geometric distortions, because during the data registration the platform is off-nadir [7]. Besides them during SAR data processing additional parameters such as type of the orbit, position of the satellite during the acquisition, internal parameters of the instrument, etc. are different for each acquisition and must be accounted too. To this end this information available in a form of metadata in the SAR data product and must be used during the processing in order to obtain correct results for the behaviour of the studied surface areas [8].

The information concerning the ground deformations that took place in the studied region was obtained by using the repeat-pass interferometry approach [9]. This method uses two SAR images obtained at different dates to form an interferometer the data from which after differential interferometric processing form an image based on the phase component of the backscattered radar signal. Besides the interferogram as separate image band produced are the values for coherence, which is used to estimate the quality of the interferometric band. After removing the contribution of the underlying topography from the interfrometric image we infer conclusions on the occurred surface motions [10]. For the last procedure DEM with spatial resolution comparable with or better than single ground element is needed and is a prerequisite for the processing. To improve the interferometric results additional processing steps were performed such as spatial filtering and multilooking. To transform the phase values from the range [-π;+π] to a metric unit a phase unwrapping must be carried out (see [6]). Concerning the unwrapping process, we followed the recommendation made in [11] to process smaller portions of interferometric image in order to avoid low coherent areas. From the unwrapped phase the displacement values in LOS (the line denoted with R in Fig. 1) were produced. Finally, a transformation to a desired geodetic datum was performed enabling the displacement images to be analyzed in GIS or other software as well. All mentioned processing steps were realized in the Sentinel-1 toolbox of SNAP software developed by ESA.

Serious advantage of the SAR data compared to the optical imagery in landslides monitoring is the ability to create inventory maps shortly after a landslide event despite of the weather conditions and in absence of illumination from external source. This fact is confirmed by the growing number of new satellite missions that will deliver SAR data at different wavelengths (X, C and L bands) with single or dual polarization, with improved spatial resolution (less than 1 m) and short revisiting time (daily or less in case of SAR constellation).

3.2 DInSAR and photogrammetry for landslides movements

In the last decades satellite SAR data processed by differential interferometry was used in landslides inventories The InSAR method attracted the professionals from different fields delivering monitoring of wide areas, much higher point density, and most important low dependency on geography of the investigated areas and on weather conditions in comparison with the optical remote sensing, GNSS and terrain investigations. Further development of the mentioned approach is Multi Temporal Interferometry (MTInSAR or MTI) methods (e.g. Persistent Scatterers Interferometry (PSInSAR); Small Baseline Subset (SBAS)).

In the recent years the photogrammetry benefitted from latest achievements in UAS technology which made possible their integral use with PSInSAR. This approach was also used by the authors to research the latest surface movements in the RA "Fish-fish" (see sub-section 4.3 below) by comparing the results by both methods.

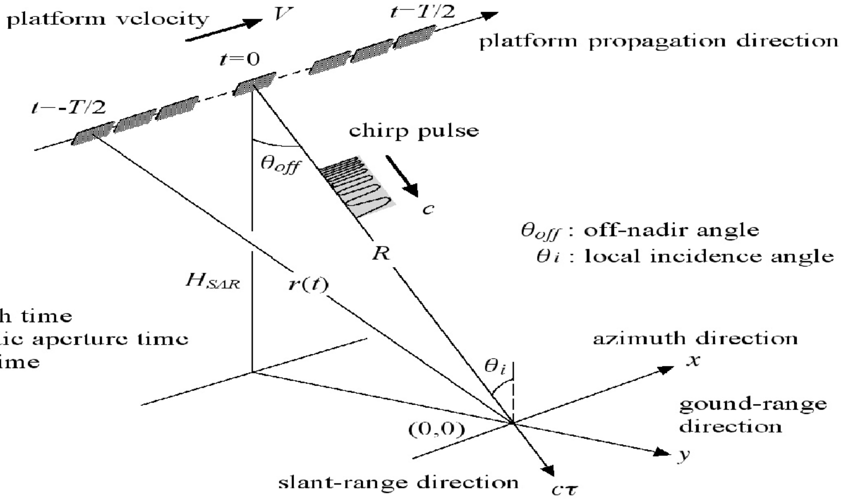


Fig. 1. Imaging geometry of a SAR sensor. (as in [6])

4. Results

The main focus of this study is on the successful application of SAR data to research the landslide movements at several areas in the region of Northeast Bulgaria. They were investigated as pilot sites in order to be able to provide reliable information on the ongoing geodynamical process in the said zone. Since the main consequence from landslides activations is movement of earth masses in horizontal and vertical directions the main data source must be a SAR data product that contains the phase component of the backscattered signal. Such data products from S-1 are those stored in Single Look Complex (SLC) format with double polarization (VV and VH) processed to Level-1 as described in. In order to facilitate the data sets selection for present and future studies in the study area the authors created and continuously update is a local archive with SLC SAR imagery starting from year 2015. This archive allowed selection of optimal interferometric SAR pairs in terms of orbit direction and suitable perpendicular baseline [12] and at present contains more than 700 data products.

Initially to produce the interferograms data from ascending and descending S-1 orbits were used, but after obtaining the first results it became evident that better results have been produced using the descending orbit only. This decision was based on the fact that larger number of areas with high values for the coherence band were obtained from that orbit. Also, for most of the investigated sites the topography caused geometrical distortions (mostly shadows), noticeable on results obtained from ascending orbit data sets, since the inclination of the slopes at the whole coastal zone is high. Other challenge, known as temporal decorrelation, that was faced is the presence of large areas covered by vegetation in the investigated zones, which decreased the quality of the produced interferograms. To this end selected for processing were only those data sets that were registered out of the growing season for the vegetation i.e. from mid-autumn to mid-spring.

One more restriction we had to consider was the size of the area that had to be processed in order to avoid large areas with low coherence since those areas have negative influence during the unwrapping transformation [11]. For this reason, to obtain correct final results after producing the interferogram only part of it is further processed based on datum coordinates of the area subject to a specific study. Besides the vegetation the studied region is specific with having maritime areas that exhibit same decorrelation effect due to sea water evaporation and this is why the water areas had to be avoided (if possible) or removed during processing as well. For this reason, in the most of the interferograms reflecting the occurred surface motions at the studied sites presented in this section the pixels that had corresponding coherence below 0.3 were removed from the final displacement images (see Figures 2, 3 and 5). One more consideration that became apparent from our research was that the VV polarization of the radar signal S-1 delivers better results compared to the VH one.

4.1. Dalgiya Yar

4.1.1. Description of the AOI

This site is quite specific since this is an ancient landslide strip almost 10 km long, which is currently broken into smaller ones. It was established that the sliding surface of all landslides starts from a plateau located about 1 km from the seashore suggesting that the prime driving factor for their activations should be the varying level of the underground waters the marine erosion almost has no impact on them. [3] It should be noted that in this area a distinctive phenomenon is observed – a smaller landslide develops inside a larger one.

For the last half century, the oldest registered activation there dates back to 1971. Due to displacement of earth masses reaching 17 m width a landslide with shaft 4 m high reaching the sea and notch up to 15 m was formed. Its perimeter was established to be 250 m in length and 800 m width thus covering an area of 2 km^2. In the next 15 years due to increased technogenic intervention (building of houses and other infrastructure) there were several other activations took place destroying some 30 houses. In this it was confirmed that geological and hydrogeological conditions are at fragile steadiness state that could be easily disrupted by construction activities. This finding was affirmed by activation of a large landslide, which resulted in collapse of tens of thousands of cubic meters earth masses along a line about 2 km long. This event completely demolished a lighthouse and buildings in a fisherman village putting in danger the seaside road Varna-Balchik. It is supposed that the main cause for this activation was the increase of the underground water levels caused of rain and snow melting, sewage water, etc.

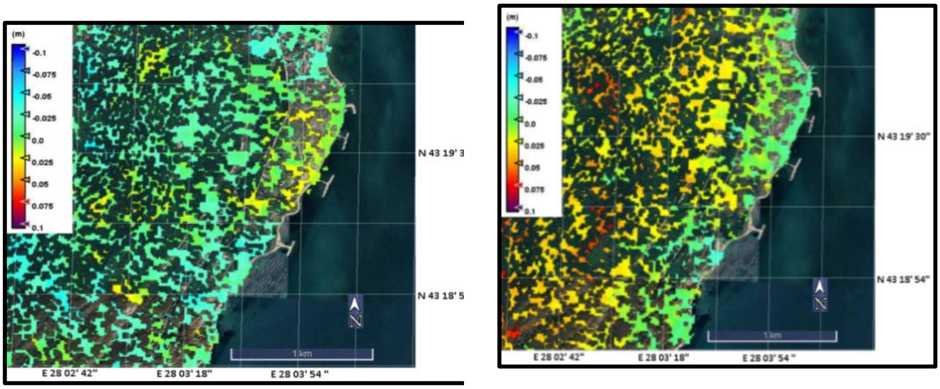
4.1.2. GNSS networks

To study the deformations due to the landslide processes in this area usage of GNSS technology has been adopted. It is based on data from two types of GNSS networks - points located on geologically stable terrain and points located in the landslide body. Data for the stable points located in non-deformable zones in the region are provided by the stations from the continuously operating reference stations (CORS) from the National GNSS Network. It needs to be highlighted that the velocities of the points from the said network in the northern Black Sea region are relatively small, less than 1 mm/year, while in other regions of Bulgaria they can reach 3–4 mm/year. To obtain the movements of the points from the purposely created local geodynamic networks their GNSS measurements were processed together with the GNSS measurements from the points of National GNSS network.

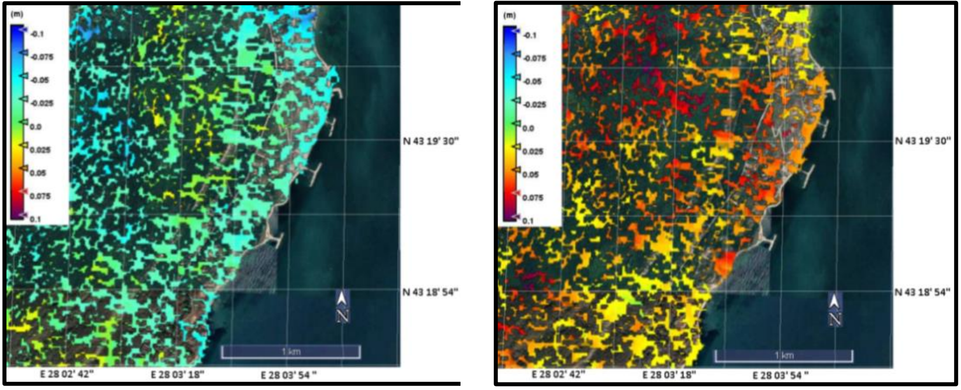
In the area of Dalgiya Yar a local geodetic network consisting of 30 points well stabilized in the ground with steel pipes or bolts was created. The GNSS measurements on this network were performed in three cycles since 2019 in the period June-July.

4.1.3. SAR results

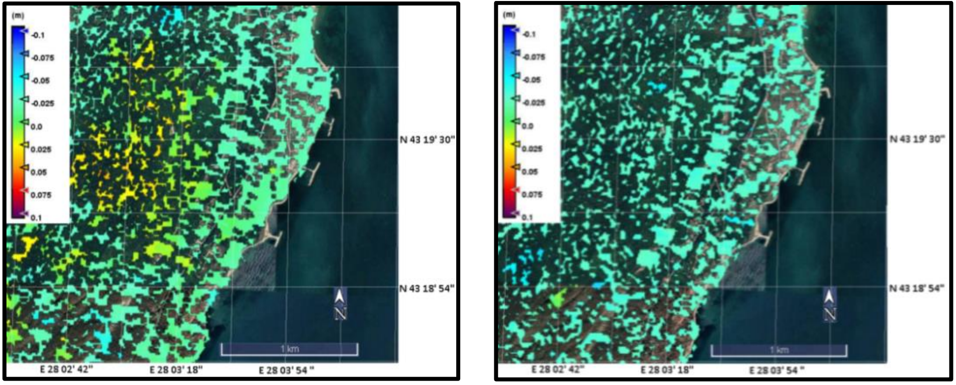
For researching this study area produced was a set of interferograms from descending orbit of S-1 only. Since the outcome of the processing is focused on surface deformations during the processing a constraint concerning the length of the perpendicular baseline for single pair was set to be less than 35 m.



a) 20Nov2015_11Mar2016 b) 26Nov2016_20Mar2017



c) 15Nov2017_27Mar2018 d) 20Nov2018_22Mar2019



e) 29Nov2019_28Mar2020 f) 23Nov2020_23Mar2021

Fig. 2. Maps of SAR-derived displacements for the winter periods from 2015 to 2021

In order to correctly compare and analyze the displacements results SAR data pairs from winter season with 4 months span that satisfy the said constraint were used. On Fig. 2 excerpts from larger interferograms over a raster layer, on which only pixels having high coherence values (above 0.3) were coloured accordingly, while the rest were left transparent (a-f).

4.2. Residential area(RA)"Fish-fish"

4.2.1 Description of the AOI

In the zone of this RA located are three landslides – one potential, one active and one stabilized. The active landslide processes at this site were first registered in year 2000 (according to local inhabitants) and as probable cause for their activation a water mains accident was pointed out. In year 2010 it developed further increasing the affected area up to 5600 m^2. After that it is difficult to provide the exact size of the landslide area due to presence of high and dense vegetation, and gradual earth masses collapses along the steep coast, but an estimate by experts affirm that currently its area is about 57000 m^2 i.e. 10 times increase since the first registration. According to the competent local authorities this landslide activated twice in the last 6 years destroying houses and other infrastructural objects.

All said underline the importance of satellite-borne SAR data to produce reliable information for the regular monitoring of the ground deformations and possible earth masses subsidence accidents at this site.

For this site again the main reason for landslide activations is the rise of the underground water level caused by different sources – torrential rains, fast snow melting, human activities. In the RA "Fish-Fish" the landslide, which developed on streets "3rd" and "4th", is registered using their names. It is located within an ancient landslide strip that starts from Albena resort and reaches the town of Balchik with a typical for this region landslide geomorphology. Currently its width is about 600–700 m and is formed on the slopes of the Dobrudzha plateau to the sea. The landslide toe has elevations of about 40–50 m ASL and forms a steep slope towards the sea [3].

The landslide on streets "3rd" and "4th" has developed above the edge of a 65–75 m high, steep 50°–60° slope towards the sea. Above the landslide scarp to the west, in the RA begins a relatively flat terrain, part of a slope with an inclination of about 5°–8° in south-southeast direction. In April 2010 its upper limit was at heights of 8.50–9.00 m on the vertical landslide slope above the sea front. The landslide is frontally extended with a length in the direction of movement of about 40–50 m, a width of 120–150 m and an area of about 5600 m^2. During the months September–October 2010 the slope reached and passed to the northeast on "2nd" street.

4.2.2. SAR results

It should be noted that an event that took place in August 2018 is well detected by SAR data, but in it was once again confirmed that the presence of high slopes in the zone hampers the registrations from ascending orbit The results obtained, despite the short period that was studied, are consistent (showing same movement in the area of the collapse) and reliable (have high coherence values). As shown on the figure below the detected deformations for smaller and larger periods confirm the expected displacements to be in the range of 0.02–0.06 m and exhibit seasonal variations. The latter evidenced by the different number of points with coherence values above 0.3.

Besides using SAR data, the RA “Fish-fish” was researched within two UAS campaigns (first on June 22nd 2019 and the second on Nov 25th 2020). Both campaigns were carried out with the aim to establish the displacements in the area for the mentioned period. But it needs to be emphasized that for regular and long-term monitoring of this site the UASs has the disadvantage that they depend heavily on the weather conditions such as strong gusts and need external illumination having an optical payload. Nevertheless, they could provide data with high spatial resolution for zones inaccessible for terrain measurements – for this specific object the area between the affected zone and the seashore has parts where the inclination reaches 60^0 at some locations. This why under certain assumptions it could be appropriate to substitute the GNSS measurements in local geodetic networks with UAS acquisitions.

In order to compare and analyse the results obtained by UAS and satellite SAR acquisitions with regard to the ground motions occurred in the landslide zone for time interval of 1 year and 5 months (between both UAS acquisitions) a number of interferometric images were produced at different intervals in order to compare the values obtained by both methods.

To estimate the degree (respectively the influence) of the temporal decorrelation caused by the large time intervals to the DInSAR results the authors experimented by creating a set of interferograms at different monthly intervals (see Fig. 4). On Fig. 4 b) presented are the displacements obtained from SAR data for the whole period of 1 year and 5 months where it can be seen that the decorrelation effect is visible since the obtained values are in the interval [- 0.04; 0.02] m which is comparable with those for much shorter periods (two months e.g. Fig. 4 h) and for this reason it should not be considered as reliable. For this site the results seen on images e) and j) on Fig. 3 confirm the contribution of high decorrelation in the results in case the time period between the SAR registrations is too large e.g. one year or 8 months. The remaining excerpts (Fig. 3 d, e, g, h, i, and k) are considered as correct representation of the ground motions occurred in the mentioned periods.

4.4. “Thracian Cliffs”

4.4.1. Description of the AOI

The activations in this landslide site could be attributed to large degree to the human activities in a narrow (less than 5 km) coastal area between the villages of Topola and Bozhurets. The landslide Thracian Cliffs has developed on the coastal slope located before the entrance of the golf club having the same name (see Fig. 4a).

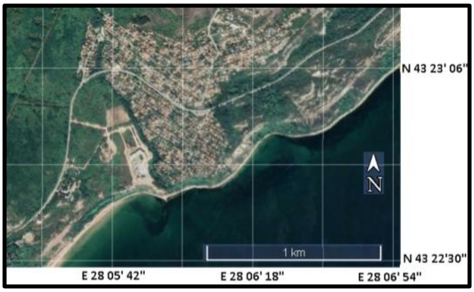
The landslide Thracian Cliffs was first registered in 2014 and has manifested in front of an ancient stabilized landslide, known as "Kalkan Tepe". The researched landslide has a width of 1500 m and a length (in the direction of its movement) of about 500 m. The landslide scarp has a height of about 50–80 m, the landslide toe is manifested in the sea and is probably blurred. The coastal cliffs in the area are 20–30 m high, almost vertical, and not forested. The main reasons for the activation of landslide processes are over wetting of the earth masses by waters of unknown origin (possibly underground, fed by domestic ones), leaks from the compromised sewerage system built on the way to the golf complex, sea erosion and possibly others [3].

4.4.2 GNSS and SAR results

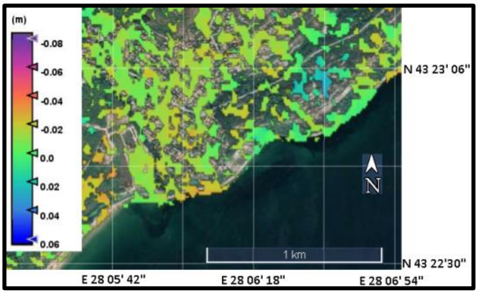
During the last 5 years this site was researched by using data from several sources - UAS acquisition (a point cloud seen on Fig. 4 a) and local DEM Fig. 4 b) local GNSS network (see Fig. 5 a). In order to establish the ground displacements with high precision a local GNSS network was created and the data from it were processed using data from the national CORSs. It included 10 stabilized points used to monitor deformations on the road leading to the golf club (points 601–604 on Fig. 5 a) and points located in the rocks and the path connecting the sea shore with the resort "Topola Skies" (points 503, 504, 605 on Fig. 5 a). Up to date three cycles of GNSS measurements on the local geodetic network were made in years 2019, 2020 and 2021 and all acquired data were processed and the results for the displacements registered by this method are shown in Table 1. Unfortunately, the point numbered 504 was not found (probably destroyed) after the last GNNS measurement and this is the reason in the same table to have absent values.

In 2020, a survey with a UAS was made in order to generate local DEM that could be used to improve the quality in the SAR data processing as well as to generate 3D representation of the objects in the area.

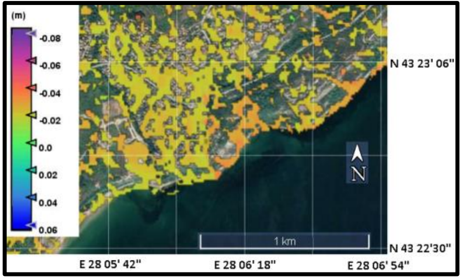
From the local SAR data archive mentioned in section 3 for this area large number of interferograms (see Fig. 5) were created covering several winter periods in consecutive years. The areas having large displacements are shown in dark blue and purple, the less vulnerable in yellow and in green are those where the displacements are smaller. From same figure derived were ground displacements in

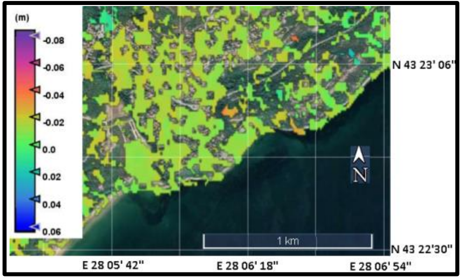


a) The surveyed area as in Google Earth



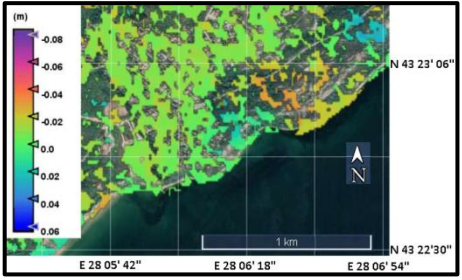
b) 20Jun2019_23Nov2020

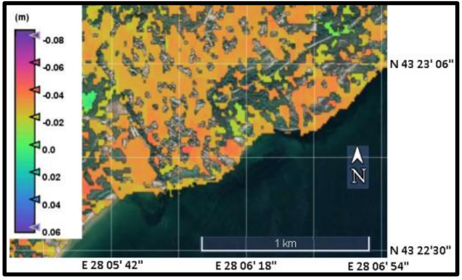




c) 20Jun2019_23Nov2019

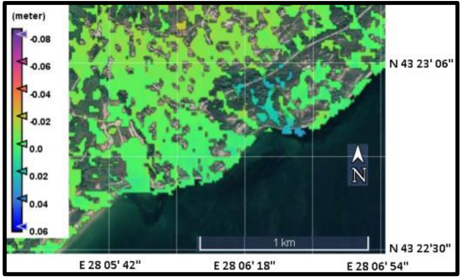
d) 23Nov2019_14Jun2020

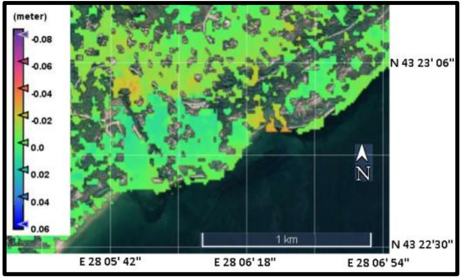




e) 20Jun2019_14Jun2020

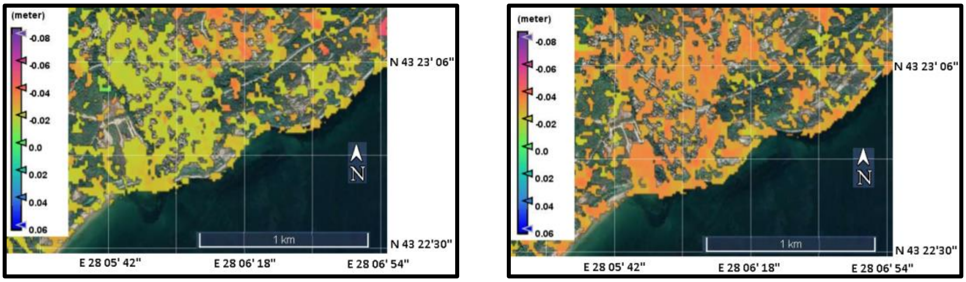
f) 14Jun2020_23Nov2020





g) 23Nov2019_22Jan2020

h) 22Jan2020_27Apr2020



i) 23Nov2019_27Apr2020 j) 27Apr2020_23Dec2020

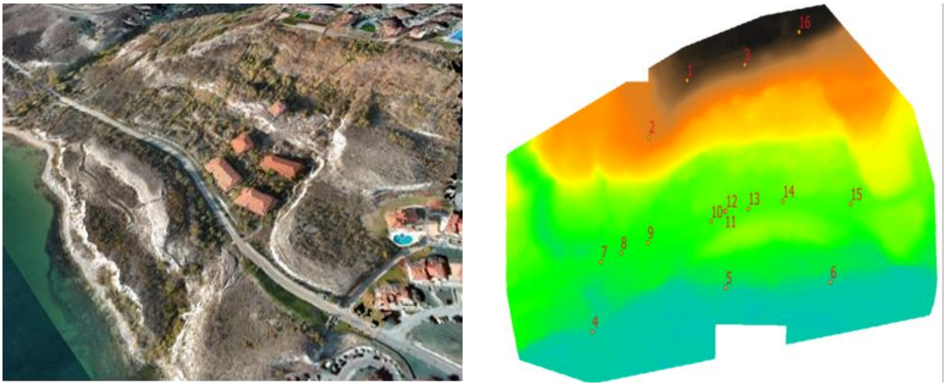
Fig. 3. Raster image of RA "Fish-fish" (a) and maps of SAR-derived displacements (b-j)

LOS the lowest value being - 8 cm. On the images b) to f) of the same figure visible is the influence of the coherence change on the final results even within same seasons, but for consecutive years. In this case even the dates for the SAR pairs are almost identical the displacements are different in different years.

5. Discussion

As mentioned in 4.1, Dagiya Yar is large site consisting of several landslide areas (some even overlapping) that was researched during the winter periods from 2015 to 2021 and the overall inference from the SAR results presented on Fig. 2 is that landslides movements vary from one period to the next. In our investigations we narrowed our focus on a small strip being 0.5 km wide that starts from the sea toward mainland and where the local geodetic network was established and measured. For this strip the obtained results for each of the winter periods the dominant movement is uplift with observed maximum the period for 2018–2019 amounting to 0.075 m.

In the area of RA "Fish-fish" it was of interest to register the development of an active landslide as well as possible activation of a potential one. For this site we made an experiment to correlate results from SAR and UAS. This experiment confirmed the need for more frequent UAS yearly campaigns (e.g. every 6 months – one in mid-autumn and one in late spring) in order to provide more data for the period into which landslide activations are more likely to occur and the time interval is not too large the temporal decorrelation to decrease the quality of the SAR-derived information.



a) b)

Fig. 4. 3D representation of the site from point cloud data a) and a local DEM overlaid by the GNSS RTK points used in UAS survey b)

The landslide Thracian Cliffs was researched via GNSS starting in 2019. From the results provided in Table 1 it is evident that the vertical movements are not constant and even for the periods 2020–2019 and 2021-2020 are showing different behaviour changing from subsidence to uplift.

Table 1. Displacements obtained by processing data from three GNSS measurement cycles

	2020-2019			2021-2020			2021-2019		
point	ΔX [m]	ΔY [m]	ΔH [m]	ΔX [m]	ΔY [m]	ΔH [m]	ΔX [m]	ΔY [m]	ΔH [m]
501	-0.032	0.002	-0.054	0.042	-0.03	0.087	0.01	-0.028	-0.067
502	0.007	-0.004	-0.019	0.008	-0.03	0.005	0.015	-0.034	-0.014
504	0.007	0.016	0.01	–	–	–	–	–	–
601	-0.025	0	-0.032	0.011	-0.033	0.064	-0.014	-0.033	0.032
602	-0.022	-0.018	-0.024	0.01	-0.028	0.066	-0.012	-0.046	0.042
603	0.005	-0.013	-0.017	-0.004	-0.034	0.058	0.001	-0.047	0.041
604	0.007	-0.006	-0.032	-0.003	-0.038	0.08	0.004	-0.044	0.048
605	-0.011	0.004	-0.032	0.008	-0.04	0.06	-0.003	-0.036	0.028

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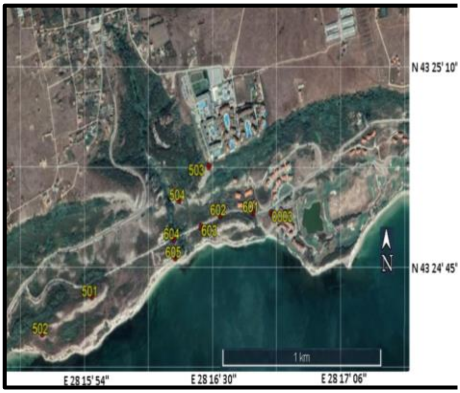
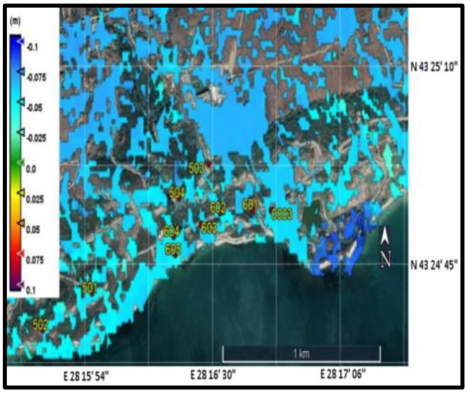
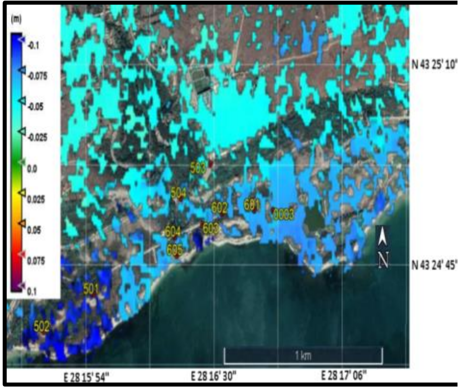


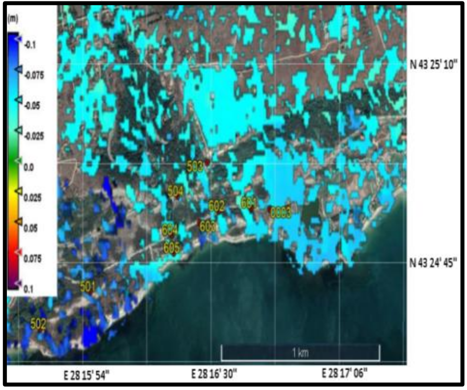
a) the local geodetic network



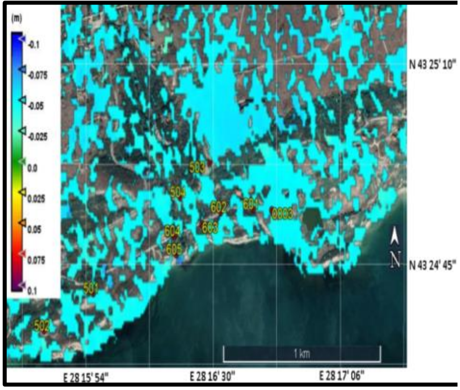
b) 20Nov2015_22Mar2016



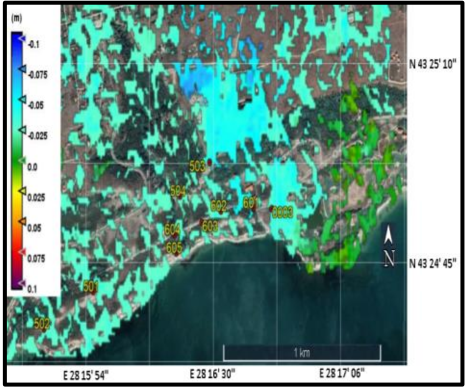
c) 15Nov2017_27Mar2018



d) 20Nov2018_22Mar2019



e) 29Nov2019_28Mar2020



f) 23Nov2020_23Mar2021

Fig. 5. Displacements registered at the landslide Thracian Cliffs for the period 2015–2020

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МОНИТОРИНГ НА КРАЙБРЕЖНИТЕ СВЛАЧИЩА ПО СЕВЕРОИЗТОЧНОТО ЧЕРНОМОРИЕ НА БЪЛГАРИЯ БАЗИРАНО НА ДАННИ ОТ РАДАРИ СЪС СИНТЕЗИРАНА АПЕРТУРА

Хр. Николов, М. Атанасова

Резюме

Геоложките условия по Североизточното Черноморие на България са благоприятни за възникване и развитие на свлачища. Тези процеси са документирани през последните петдесет години в рамките на научни и научно-практически разработки на учени в различни области от направление

„Науки за Земята“. В по-широк контекст техните усилия допринесоха за опазването на ландшафта и намаляване на рисковете за населението, причинени от споменатите явления. В тази статия получените резултати показват времевото поведение през последните пет години на няколко свлачища, разположени в посочения регион. Основният източник на данни за наблюдение на споменатите свлачища са данни от радар със синтезирана апертура (PCA), обработени по метода на диференциалната интерферометрия на PCA данни (DInSAR). Въпреки средната пространствена разделителна способност на използваните данни те позволяват да бъдат създадени дълги времеви редове и да се правят изводи по отношение на преместванията на земната повърхност. Получените резултати са валидирани с помощта на измервания чрез глобалната навигационна спътникова система (ГНСС), които бяха проведени в специално създадени локални геодезични мрежи, сателитни изображения с висока пространствена разделителна способност в оптичната част на електромагнитния спектър, както и цифрови изображения, получени от безпилотни летателни системи (БЛС). Резултатите представени в тази статия, недвусмислено потвърждават, че получената информация е от важно значение за местните власти и други заинтересовани страни, като по този начин допринасят за подобряване на действията, които се предприемат при управление на риска от свлачища, както и за по-добро планиране на териториите, където са разположени изследваните свлачищни обекти.